"DAY 1" PHYSICS AT RHIC: PREDICTIONS FROM RQMD

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I discuss predictions based on the transport theoretical approach "relativistic quantum molecular dynamics". They can be tested rather soon by the upcoming experiments at the Relativistic Heavy Ion Collider at BNL (RHIC). Here I focus on the question whether hadronic observables are sensitive to the Equation of State (EOS) in the ultradense matter. A new version of RQMD has been developed recently in which the EOS can be varied, for instance like the one observed in lattice gauge studies. It is found that – somewhat paradoxically – the partial transparency of the two nuclei provides new avenues to assess the influence of baryon number in hot matter. One of the signals which are most sensitive to the dynamics is the directed flow of nucleons. As a function of rapidity it changes its direction three times. Surprisingly, even one of the most simple observables – the average transverse momenta or slopes – displays some significant sensitivity to the EOS in the phase transition region between hadronic and quark matter.

1 Introduction

With experiments at the Relativistic Heavy Ion Collider at BNL (RHIC) upcoming soon, heavy ion physics enters a new stage. It is expected that the energy densities which may be created are favorable for the creation of so-called quark-gluon plasma (QGP). Observation of this state and the transition between QGP and hadronic matter is the foremost goal of the ultrarelativistic heavy-ion program started more than a decade ago at CERN and at BNL with fixed-target experiments (beam energies up to 200 AGeV). Indications from these experiments show some clear deviations from "linear" pp and pA extrapolations which are attributable to interactions of the strongly interacting matter during its dense stages (charmonium suppression, excess dileptons, transverse flows and strange anti-baryon enhancement) [1]. In view of these promising signals it is very important that Au(100AGeV) on Au(100AGeV) collisions as planned at RHIC will provide the opportunity to study a system which – initially – may be even deeper in the quark-gluon phase than at the lower beam energies. Of course, with lack of data it is not easy to estimate the initial energy density. From an extrapolation based on the ratio of produced charged particle densities at midrapidity in pp and $\bar{p}p$ respectively (2.4:1.5) one would expect a sixty percent increase. Such a naive scaling with dN/dy of the elementary system is actually borne out by the calculations with the RQMD model [2]. In Fig. 1 the time evolution of energy density (together with the

pressure) is compared between heavy-ion reactions at SPS and at RHIC en-

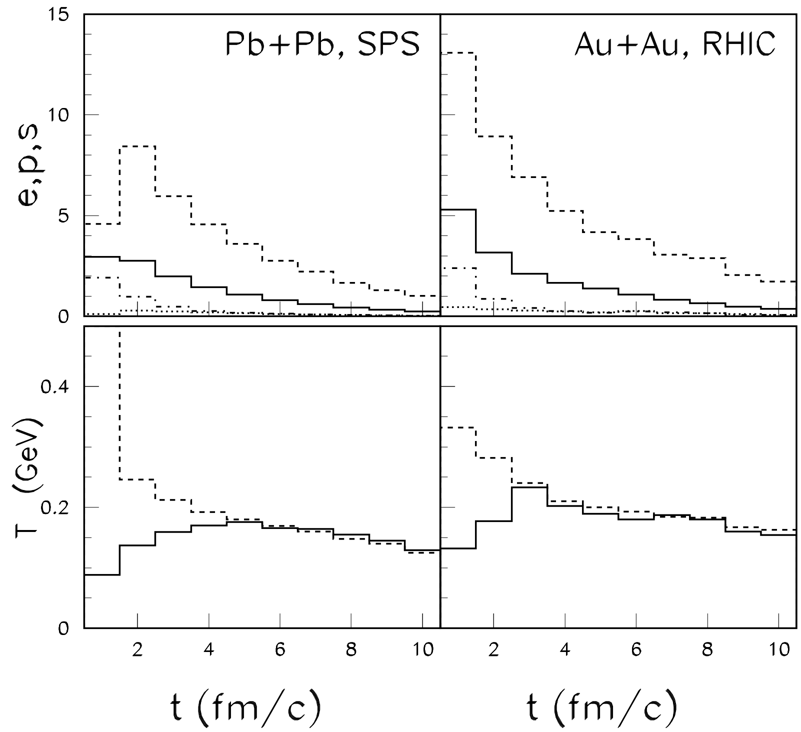

Figure 1: Comparison between Au(100AGeV) on Au(100AGeV) at RHIC and Pb(158AGeV) on Pb at SPS. The RQMD calculations were done utilizing a resonance matter EOS. Upper panel shows time evolution of pressure p (dashed-dotted line= longitudinal, dotted line= transverse), energy density e (solid line) and entropy density s (dashed line) in the collision center. The lower panel shows the "temperature" T extracted from the diagonal components of the energy-momentum tensor and the particle density. It coincides with the real temperature only after the pressure becomes isotropic and longitudinal T values (dashed line) coincides with the transverse values (solid line).

ergy. It shows that the RHIC collisions produce the denser and hotter system. From the lower panel of the Figure it may be read off that the thermalization proceeds faster at RHIC (after 3fm/c versus 5fm/c for the SPS energy). The dynamical reason for faster equilibration is that the role of the ingoing baryons is diminished with higher beam energy. Since these are transported from the original rapidities to midrapidity, they tend to cause stronger non-equilibrium effects. In contrast, produced particles are locally correlated tighter in rapid-

ity. Fig. 1 also shows that after equilibration the system stays at temperatures above $T_c \approx 160$ MeV in the center for 6 fm/c.

On the theoretical side, the "Achilles heel" of the search for the QGP and the transition is an uncertainty what the properties of the QGP are. Smilga among others has pointed out that the physics of the state above and close to T_c is a theoretical "no man's land" [3]. Neither perturbative QCD nor interactions between (quasi-)hadronic states appear justified for a description. If one can write down no equations and give no numbers the question whether one has actually "seen" a QGP may deteriorate into an exercise in semantics. One way out is to resort to models of QGP and the phase transition. For instance, J/Ψ suppression was initially predicted by Matsui and Satz as due to static color screening between heavy quarks in the plasma [4]. Lateron, J/Ψ suppression was indeed observed in Pb(158AGeV) on Pb collisions (and before in lighter systems). The model predicts that the χ states which are orbital excitations feeding into J/Ψ are even more suppressed than the Ψ' – in conflict with the observations. Do we infer that the model fails for heavy-ion reactions or that no QGP has been produced at CERN-SPS energies?

2 Radial and directed collective flow at RHIC

Another way out of the difficulty to find signatures of the QGP is to design "robust" observables which do not rely on detailed assumptions. Here one class of observables – real photons or dileptons emerging from virtual photons – can be primarily viewed as a tool to extract the highest temperature from the photon and dilepton spectra. Unlike hadrons, even early produced photons leave the system without much disturbance. The other main tool to store information from the early stages is collective transverse flow. Essentially, the flow velocities can be represented as a time integral over the forces acting on the matter during evolution. Close to equlibrium, these forces are determined by the pressure gradients (and, unfortunately, some non-ideal properties of the matter like viscosities). The pressure is a fundamental thermodynamic quantity and shows a rather characteristic behaviour in the (phase?) transition region between hadronic and quark matter. The EOS displays a "softest point" leading to a minimum of the expansion velocity [5]. In order to infer information on the acceleration history one needs to de-convolute the accumulated flow. Various techniques are available such as different types of flow which have different sensitivity to the early reaction stages (elliptical and directed versus radial flow) [6,7] and utilizing different particle species. In particular, multi-strange hadrons have typically smaller cross sections and thus decouple from the system at earlier times [8,9].

An obvious question for collisions at RHIC energy is whether the physics of the "softest point" is not better studied at lower energies. Presumably, the EOS is softest at energy densities around 1 GeV/fm^3. Indeed, various questions are currently being pursued like its influence on elliptical flow or the chemistry in AA collisions with beam energies as low as 2 AGeV. On the other side, it is one thing to infer "softening" of the EOS from data [10]. It is quite more convincing evidence for the "phase transition" (which may in fact be just a smooth cross-over) to observe the re-hardening of the EOS at larger energy densities as well. From lattice results and general considerations an asymptotic energy density – pressure relation like $p \sim e/3$ is inferred, characteristic for an ideal gas of massless quarks and gluons. How can we observe whether the system's evolution is partially characterized by such a hard EOS? The flow develops as an integral over time whose characteristic scale is set by the transverse size of the system. The hardness of the EOS at times around r_{tr}/c is more relevant concerning flow development than the degree of equilibration and the resulting maximum energy densities just after impact ($t \leq 1fm/c$). A look at Fig. 1 will tell that RHIC may be in a better position than the SPS program for studying the EOS above T_c. Typically, results of dynamical calculations (transport or hydrodynamical) agree that there is not much sensitivity to the re-hardening of the EOS up to the highest SPS energy [11,12]. Only recently it was suggested that perhaps the "kinky" centrality dependence of elliptical flow may provide evidence for a valley-type structure of p/e, i.e. the softening and re-hardening of the EOS [13]. Of course, the smaller characteristic size in semi-peripheral collisions is helpful. It is much easier to observe early-time phenomena in small systems. Several recent studies find that elliptical flow is a useful and measurable observable at RHIC as well [14,15,16].

Fig. 2 displays the rapidity distributions of nucleons, anti-nucleons and pions in Au(100AGeV) on Au(100AGeV) collisions at $b = 3$ fm as calculated from RQMD. According to the calculations the in-going baryons end up mostly in-between midrapidity and the original rapidities. In RQMD and other sensible models of baryon stopping the colliding nuclei become more transparent to each other with higher beam energies. It is usually assumed that the fast valence quarks are mere spectators in the soft reactions which are initiated by the soft glue $x_F \to 0$. Thus leading particles obey Feynman scaling which translates into a scaling rapidity loss distribution at high energies. For baryons the average loss is $\Delta y \sim -2$ in central heavy-ion collisions. It is one of the intriguing aspects of the baryon stopping that shift of baryon number and valence quarks may not coincide. (It has not been checked for real collisions, but in the model they do not. "Net-valence" distributions constructed from e.g. net kaon distributions show more transparency than the net-baryon dis-

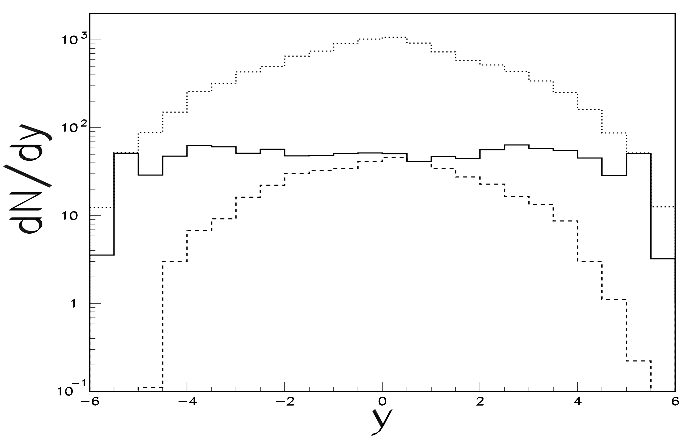

Figure 2: RQMD result for the rapidity distribution of nucleons, anti-nucleons and pions in Au(100AGeV) on Au(100AGeV) collisions at $b = 3$ fm.

tributions.) In a model like RQMD the "junction" which connects the $N_c = 3$ valence quarks via "strings" is an independent dynamical object [2]. If all valence quarks are stripped off the junction, the emerging baryon is stopped more than the valence quarks. (There have been other talks in this meeting devoted to the subject of baryon stopping, e.g. Huang's talk.)

A small value of net-baryon rapidity density leads to small spatial net-baryon densities in the central region. However, with the baryon densities peaked off midrapidity a strong gradient of baryon density with increasing rapidity is created. Using the idealizing equilibrium assumption, going away from y=0 corresponds to walking to finite μ_B in the T-μ_B plane. It allows to obtain information on the phase diagram of QCD by correlating baryon number in different rapidity windows to observables, possibly even event-by-event. Fig. 3 shows that the role of baryons may have striking consequences for "radial" transverse flow (the dominating isotropic component). In the figure the average transverse momentum of protons is shown as a function of rapidity calculated with RQMD. The average p_t of nucleons serves as an experimentally accessible proxy for the not directly observable radial expansion. Two results are compared, one obtained with a resonance matter EOS ($p/e \sim 6$), the other based on an EOS with 1st order phase transition [13]. It was calculated in a bag-type model of quarks and gluons with temperature-dependent masses and "bag constant" which agrees well with lattice data (small latent heat). We observe that the flow (average transverse momentum) is larger at non-zero rapidity – contrary to any naive ideas about "more action in the center" and observations at fixed-target energies. At midrapidity both EOSs lead to the same hardness

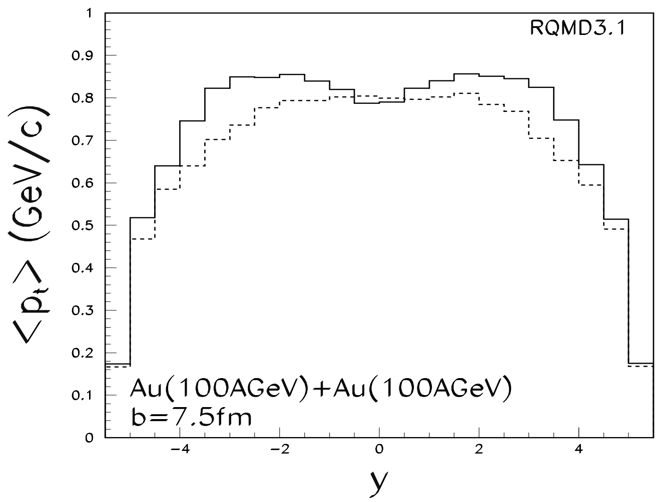

Figure 3: Average transverse momentum of nucleons as a function of y: EOS w. 1st order phase transition (solid line), resonance gas (dashed line).

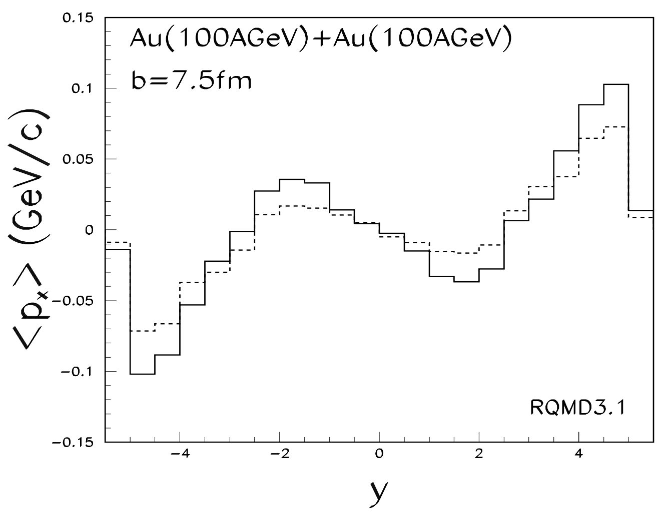

Figure 4: Average transverse momentum component of nucleons in the reaction plane as a function of y (directed flow): EOS w. 1st order phase transition (solid line), resonance gas (dashed line).

of the transverse momenta. Additional hardness of the EOS in the quark-gluon phase is canceled by the softness in the "mixed" phase compared to the structureless resonance matter EOS. The very good agreement of resonance gas dynamics with data as observed at SPS energy (158–200AGeV) [7] may have been accidental to some extent, by hitting just the right average pressure. At RHIC – away from midrapidity – adding baryons destroys the balance between additional hardness and softness increasing the total amount of flow.

Another handle on the EOS in the ultra-dense matter is provided by the so-called directed flow (a "kick" of matter in the reaction plane which is balanced by the corresponding "anti-kick" at opposite rapidity. Fig. 4 displays the calculated average transverse momentum component of nucleons in the reaction plane as a function of y. From fixed-target energies the S shape of $p_x(y)$ is well-known. For collider energies RQMD predicts a more complicated structure [17]. The two wings of the "S" are still present close to the projectile and target rapidity respectively. However, the "S" is broken into two pieces. Nucleons at more central rapidities tend to move into the opposite direction from their fellow nucleons in the same hemisphere. The dynamical reason for this unorthodox behaviour is the inhomogeneous transverse source distribution of the ingoing baryons after the initial impact. The large rapidity gap between projectile or target nucleus and central rapidity region can only be overcome if nucleons pass through as much nuclear matter as possible. That is just the side opposite to the spectators comoving in their direction which define the standard S shaped configuration. Furthermore, the large gap of five units in rapidity means that typically nucleons stay in their rapidity hemisphere even if they are close to midrapidity. Therefore ingoing baryons find themselves on opposite sides of the reaction zone depending on the sign of their rapidity (in the center of mass). The subsequently developing transverse flow converts the initial directional asymmetry in the reaction plane into a directed flow signal. In Fig. 4 the results for the EOS with 1st order phase transition are compared to the results with the resonance gas EOS. It becomes apparent from a comparison with the results for average transverse momenta that the transverse momentum component in the reaction plane is clearly more sensitive to the EOS. Uniformly, the directed flow is more pronounced with the QGP based EOS which points to a larger sensitivity to the early evolution for this observable.

3 Conclusions and Disclaimer

Of course, some caveats are in order about the calculations. The QGP based EOS has been implemented in the RQMD model as $p(e)$, i.e. baryons con-

tribute only implicitly – via their energy. This prescription does not need to be true. We do not know too much about the EOS of QCD at finite temperature and baryon density. Basically, there are two schools of thought, one empirically oriented and one studying simple models (NJL etc.) which resemble QCD. One can constrain the baryon density dependence of the EOS from heavy-ion reactions at beam energies down to very low values (∼1–10 AGeV, the AGS region). This has been done in the past by many people. The debate is not closed yet and oscillates between preference for a "hard" versus "soft" EOS (with a remarkable come-back for the former) [18,19]. A recent variation of the "hard versus soft" debate is that perhaps the EOS is hard first but softens with increasing baryon density [20]. It should be noted that the scale defining "softness" is very different from the baryon-number suppressed high-energy (SPS) scale. On the low-energy (=baryon-rich) scale a resonance gas EOS is actually ultrasoft and ruled out by plenty of data in the energy range 1–15 AGeV [21]. The bottom line from HI physics is therefore that baryons make the EOS more repulsive compared to baryon-free matter at same energy density. An interesting consequence could be that a 1st order(-like) transition at μ_B=0 is "killed" by adding baryon number. On the other side, based on NJL-type models we expect just the opposite, an almost 2nd order transition at μ_B=0 (almost because of the nonzero masses of light flavor quarks) and a 1st order transition at T=0 and finite μ_B. An interesting consequence would be that the 1st order transition line ends in a tri-critical point somewhere in the $T-\mu_B$ plane[22]. Of course, having in mind that nuclear matter exerts more pressure than pions it may be just the other way around. In that case a tri-critical point would be connected to T_c at μ_B=0 via a 1st order transition line. More detailed studies of this possibility are currently under way [23]. Lattice calculations are not conclusive yet about the nature of the transition at finite T. The mass of the strange quark is the decisive factor. Yet another phase transition at finite baryon density may be associated with a super-conducting phase of QCD in which color symmetry is spontaneously broken [24,25]. However, this phase is probably not accessible in heavy ion collisions, because they are too hot. It has been claimed that the observed persistence of magnetic fields in neutron stars rules out such phases and the large associated gaps even at T=0 for nuclear densities in the range of up to 8 ρ_0 [26]. In any case, some clarifications of the QCD phase diagram at high T and – depending on rapidity window – zero or nonzero μ_B may be within reach with the upcoming RHIC experiments.

Acknowledgments

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